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ESTIMATING SEISMIC PARAMETERS ASSOCIATED WITH PREVIOUS EARTHQUAKES BY SCPTU SOUNDINGS IN THE NMSZ

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ABSTRACT

Although the New Madrid seismic zone (NMSZ) is the most active seismic region in the eastern United States, paleoliquefaction features are often used to analyze the previous seismic activities, due to the long recurrence interval of large earthquakes. A new methodology is proposed in this paper to estimate the seismic parameters associated with previous earthquakes based on the results of seismic cone penetration tests (SCPT), using the simplified procedure of liquefaction analysis and the attenuation relationships developed for the corresponding seismic areas. This methodology is validated through the paleoliquefaction studies at two sites associated with the 1989 Loma Prieta earthquake (Moss Landing and Yueba Puena Cove). It is then applied to estimate the magnitude and peak ground acceleration (PGA) for the major previous earthquakes in the NMSZ.

INTRODUCTION

Upon liquefaction, saturated loose sands tend to flow upward and vent to the ground surface. Vented sand deposits that formed at the ground surface due to previous earthquakes have been widely observed in the New Madrid Seismic Zone (e.g. Obermeier, 1998). However, measured strain rates, which indicate how fast the lithosphere is being deformed during plate tectonic movement, in the NMSZ are relatively low (Newman et al., 1998). As a result, the recurrence interval of large earthquakes in NMSZ is relatively long, and is suggested to be hundreds of years (Tuttle & Schweig, 1995). Since even the most recent large earthquakes occurred nearly two hundred years ago, their surface traces, such as sand boils, subsidence, and dikes, have been modified by erosion, farming, vegetation, and other manifestations, thus making them very difficult to identify. Therefore, paleoliquefaction features, which are formed during past earthquakes and kept within the soil stratigraphy, are often used to analyze the previous seismic activities.

Both geological and geotechnical methods have been used in paleoliquefaction studies to back-calculate the seismic parameters associated with previous earthquakes (e.g. Martin & Clough, 1994; Pond, 1996). In this paper, a new methodology has been proposed for estimating these parameters based on seismic cone penetration tests (SCPT). It has been applied to the 1989 Loma Prieta earthquake in California, as well as previous earthquakes that occurred in the New Madrid Seismic Zone (NMSZ) using the SCPT data collected throughout this region (Fig. 1).

Fig. 1. Representative CPT locations in NMSZ

METHODS TO ESTIMATE SEISMIC PARAMETERS

A very important task of the paleoliquefaction studies is the estimation of seismic parameters associated with previous earthquakes. Obermeier & Pond (1999) and Tuttle (2001) summarized a number of techniques which can be used for back-calculating the degree of shaking and magnitudes of earthquakes from paleoliquefaction features. Basically, these techniques can be divided into two categories: 1) the geological methods that assumes that distribution of liquefaction features is related to the characteristics of earthquakes; 2) the geotechnical methods that considers both ground shaking and soil properties as the prerequisites of liquefaction.

The geological methods include: (1) the liquefaction severity index (LSI) method based on the relationship between the LSI and the epicentral distance (Youd & Perkins, 1987); (2) the magnitude-bound method based on the relationship between the magnitude and the maximum epicentral distance of surface evidence of liquefaction (Ambraseys, 1988); (3) the energy-stress method based on the relation between the seismic energy intensity and penetration resistance of soils (Pond, 1996); and (4) the comparison approach that reconstructs the paleoearthquake event by comparing the paleoliquefaction features with those resulting from other earthquakes in the same region (Tuttle, 2001).

With the geological methods, it is generally assumed that sand blows of large size are located in the area where strong ground shaking occurs. However, liquefaction is triggered by the full or partial collapse of the sand-grain structure caused by the ground shaking during earthquakes. Then, the locally-liquefied material will cause stress redistribution in the surrounding soil mass, inducing larger scale liquefaction (Gu, et al., 1993). This process is not only related to the characteristics of earthquakes, but also the local site conditions, such as the layering and related soil properties. Evidence found from some recent earthquakes confirms that the distribution of liquefaction features can be irregular (Tuttle, 1999). Therefore, it is reasonable to employ geotechnical methods for paleoliquefaction studies, since they consider both the ground shaking and the soil properties.

The geotechnical methods that have been used to estimate seismic parameters include: (1) the simplified procedure based on the relationship between the peak ground acceleration (PGA) and the penetration resistance of soils, typically the blow counts of the standard penetration test (SPT) (Seed et al., 1983, 1984, 1985); (2) the cap thickness method based on the relation between the thickness of liquefied layer and the overlying non-liquefied cap for certain PGA (Ishihara, 1985).

Using both the simplified procedure and the cap thickness method, Martin & Clough (1994) conducted research to estimate the seismic parameters associated with the large historic earthquake that occurred near Charleston, South Carolina in 1886. However, the cap thickness method was developed from data collected from two major earthquakes in Japan and China (Ishihara, 1985). Thus, its validity for other earthquakes and other regions still needs to be justified. More recent analysis found the criteria are valid only for liquefaction sites that are not susceptible to ground oscillation or lateral spreading (Youd & Garris, 1995).

By judging if the soil at a given site has liquefied or not during earthquakes, the simplified procedure relates the peak ground acceleration (PGA) with the soil properties, which are represented by penetration resistance of the field tests. Although this relationship is also based upon case histories collected outside of eastern North America, it focuses on the mechanical properties of soils under ground shaking, and therefore will be less sensitive to geologic and tectonic setting of the investigated region. The widely-used SPT N-value has been used to provide an evaluation of the resistance of soils to liquefaction. However, the test is quite variable due to energy inefficiency amongst different drillers and equipment. As an alternative, the seismic cone penetration test (SCPTu) can provide better quality data. In addition, both normalized tip resistance (q_{T1}) and shear wave velocity (V_{s1}) are obtained from the same sounding, and therefore allow for the independent assessments on liquefaction potential. The SCPT is best qualified to fulfill the task of paleoliquefaction analysis as the V_s profile obtained is also needed for evaluating site-specific ground shaking (i.e., CSR or a_{max} = PGA) from amplification analysis. Hence, the SCPTu test is used herein to evaluate the seismic parameters associated with the previous earthquakes that occurred in NMSZ.

METHODOLOGY FOR ESTIMATING SEISMIC PARAMETERS BY SCPTU TEST

Existing correlations for evaluating liquefaction potential based on in-situ tests were developed almost exclusively from post-earthquake data (Chameau et al., 1991a; Olson et al., 2001). However, pre- and post-earthquake measurements can be significantly different (Chameau et al., 1991a). Since the existing liquefaction correlations are based on in-situ data measured after earthquakes, they are more appropriate for back-calculation of the seismic parameters associated with previous earthquakes.

The seismic loading is typically expressed in terms of cyclic stress ratio (CSR) that represents the normalization of cyclic shear stresses to effective overburden stress (Seed & Idriss, 1971):

$$CSR = \frac{\tau_{ave}}{\sigma_{vo}^{'}} = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma_{vo}^{'}}\right)r_d \qquad (1)$$

where a_{max} is the peak ground acceleration (PGA) generated by the earthquake of interest, g is the acceleration of gravity, σ_{vo} and σ'_{vo} are the total and effective vertical stresses respectively, and r_d is a stress reduction coefficient that accounts for the flexibility of the model soil column.

The cyclic resistance ratio (CRR) at the time when a previous earthquake occurred can be evaluated from either q_T or V_s data, using the criteria proposed by Robertson & Wride (1998) and Andrus & Stokoe (2000), respectively. During an earthquake of moment magnitude M_w, the CRR of the site can be derived from the following equation:

$$CRR = MSF*CRR_{7.5} \qquad (2)$$

where $CRR_{7.5}$ is the cyclic resistance ratio of soils in the event of an earthquake with M_w = 7.5, and the moment scaling factor (MSF) represents the effect of duration of ground shaking resulted from earthquakes. The value of MSF decreases with the increase of the magnitude, for the duration of ground shaking increases with the earthquake magnitude. The relation of MSF with earthquake moment magnitude suggested by Youd et al. (2001) is used herein.

During earthquake shaking of loose saturated sands, there is no likely liquefaction when CSR < CRR. Liquefaction occurs when CSR > CRR. Liquefaction is triggered and termed "marginal liquefaction", when CSR = CRR. By substituting both Equation (1) and (2) into CSR = CRR, the minimum peak ground acceleration (PGA) that triggers liquefaction can be derived from the following equation:

$$\left(\frac{a_{\max}}{g}\right)_{\min} = \frac{MSF \cdot CRR_{7.5}}{0.65 r_d}\left(\frac{\sigma'_{vo}}{\sigma_{vo}}\right) \qquad (3)$$

Since the MSF decreases with earthquake magnitude, it is expected that the critical PGA or a_{max} triggering liquefaction decreases with the increase of the earthquake magnitude.

The PGA can alternatively be estimated through empirical attenuation correlations of a_{max} with earthquake magnitude, distance from the seismic energy source, and local site conditions. By combining the peak acceleration attenuation relations for rocks motions with the amplification ratios at soft soil sites (i.e. the ratios of peak acceleration at a soft soil site divided by the corresponding peak accelerations at a nearby rock site), Idriss (1991b) derived the following attenuation relations for estimating the peak acceleration at soft soil sites:

For $M_w \le 6$

$$Ln(a_{\max}) = e^{(1.673-0.137M_w)} - e^{(1.285-0.206M_w)} Ln(R+20) \qquad (4\text{ a})$$

and, for $M_w > 6$

$$Ln(a_{\max}) = e^{(2.952-0.350M_w)} - e^{(2.015-0.328M_w)} Ln(R+20) \qquad (4\text{ b})$$

where a_{max} is in g's, Ln is the natural logarithm, M_w is the moment magnitude of the earthquake, and R is the hypocentral distance to the source in km. Idriss (1991b) suggested that the standard error associated with above equations is magnitude-dependent and can be estimated using the following equations:

$$\varepsilon = 1.39 - 0.14M_w \quad \text{for } M_w < 7.25 \qquad (5\text{ a})$$

$$\varepsilon = 0.38 \quad \text{for } M_w \ge 7.25 \qquad (5\text{ b})$$

Based on the estimated shear strength of soft soils under dynamic conditions, Idriss (1991b) also suggested that a maximum limiting value of 0.6 g can be applied to the PGA derived from the empirical correlations.

For eastern North America, Boore & Joyner (1991) proposed the following equation to estimate the PGA:

$$\log(a_{\max}) = 0.672 + 0.448(M-6) - 0.037(M-6)^2 - 0.016(M-6)^3 - \log R - 0.0022R \qquad (6)$$

where a_{max} is in g's. This relationship can represent the average soil conditions in the Mississippi Embayment for moment magnitude ranging from 5 to 8.5 and hypocentral distances from 10 to 400 km (Boore & Joyner, 1991). The estimated PGA increases with the earthquake magnitude, and decreases with the hypocentral distance.

The critical PGA triggering liquefaction, which is derived through liquefaction evaluation, monotonically decreases with the magnitude, while the PGA calculated using the attenuation relations monotonically increases with the magnitude. The magnitude of an earthquake event and the threshold acceleration that triggers marginal liquefaction are the value of M_w and PGA at which both relations agree. Therefore, sites of marginal liquefaction have great significance to the paleoliquefaction studies, since marginal liquefaction indicates that the driving forces caused by earthquake are equal to the resisting strength of the soil (Stark, 2001). Because CRR can be derived from both q_T and V_s, CSR and the PGA the sites have experienced can thus be back-calculated. During an earthquake event, the liquefied sites that have the greatest distance to the epicenter are also significant for estimating the seismic parameters. Generally, with the increase of distance to the epicenter, the driving force of the earthquake attenuates, and the extent of the liquefied features decreases. When the distance exceeds the limit of the liquefaction field, no liquefied sites can be found. The liquefied sites that have the greatest distance to the epicenter are located close to the boundary of the liquefaction field. Therefore, it is reasonable to believe that the M_w and PGA that triggered liquefaction at these liquefied sites were not significantly higher than, if they were not close to, the M_w and critical PGA for this site to liquefy.

VALIDATION OF THE METHODOLOGY THROUGH 1989 LOMA PRIETA EARTHQUAKE

In order to validate the methodology proposed above, the procedure is applied to back-calculate the seismic parameters associated with the Loma Prieta earthquake that occurred on October 17, 1989. This earthquake resulted from a slip along a 45-kilometer segment of the San Andreas fault where it traverses the Santa Cruz Mountains. This earthquake is a moderate event with a moment magnitude M_w = 6.9 to 7.0, and its epicenter is located in the Santa Cruz Mountains, approximately 18 km from Santa Cruz and 96km south of San

Francisco (Fig. 2). Also shown in Fig. 2 are the sites where liquefaction-induced damage occurred due to the 1989 Loma Prieta earthquake.

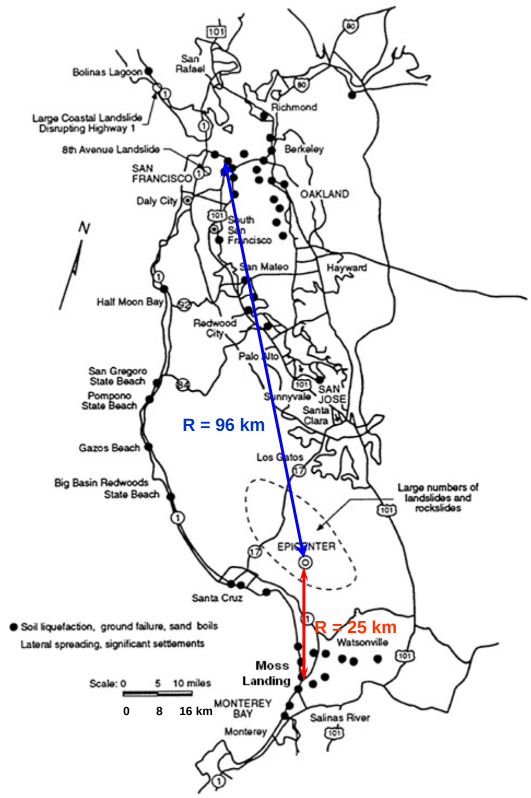


Fig 2. Regional map of liquefaction-induced damage due to the 1989 Loma Prieta earthquake (after Seed et al., 1991)

<u>Moss Landing Site</u>

During the 1989 Loma Prieta earthquake, extensive liquefaction occurred at several locations within the area of Moss Landing located on Monterey Bay in California. This area is underlain by Holocene alluvium with thickness up to 60 m, and the deposit is generally soft near the surface. Boulanger et al. (1997) suggested this area to be a soft soil site. The numerical simulations performed by Woodward-Clyde (1990) and Mejia et al. (1992) suggest that the peak horizontal acceleration on a hypothetical rock outcrop at Moss Landing should be about 0.15g. Using the relationship proposed by Idriss (1991a) for amplification of peak horizontal accelerations on soft soils relative to rock, the peak horizontal acceleration at the Moss Landing area should be about 0.2 to 0.3 g, which is consistent with the level of damage to contents of buildings and with intensity of ground motions felt by people in the area (Boulanger et al., 1997).

Slope inclinometers were installed along the shoreline edge of Moss Landing area prior to the Loma Prieta earthquake, and readings were made before the earthquake in April and June 1989, as well as after the earthquake on November 30, 1989 (Harding, 1988). Lateral displacements were noticed during this time period, and they were attributed to the earthquake effects, since prior measurements and observation showed the shoreline slope was not deforming measurably. The deflection measured by one of the inclinometers is shown in Fig. 3, along with data from a CPTu sounding performed 1.5 m away from the inclinometer. The CPTu data include tip resistance q_T, sleeve friction f_s, measured porewater pressure u_2, and friction ratio FR. The static porewater pressure is presented along u_2 for comparison purpose. The soil profile in this figure is interpreted by Boulanger et al. (1997) based on the CPTu signature and soil samples from an adjacent SPT boring performed 3.0 m away from the inclinometer. The primary deformation occurred between depths of about 2.0 and 4.5m, and the ground surface moved about 28 cm to the east and 10 cm to the north. After analyzing the CPTu results and the index data of the soil samples, Boulanger et al. (1997) concluded that the deformations resulted from liquefaction in two sand layers which are located between the depths of 2.1 m to 3.6 m and 4.2 m to 4.6 m, respectively.

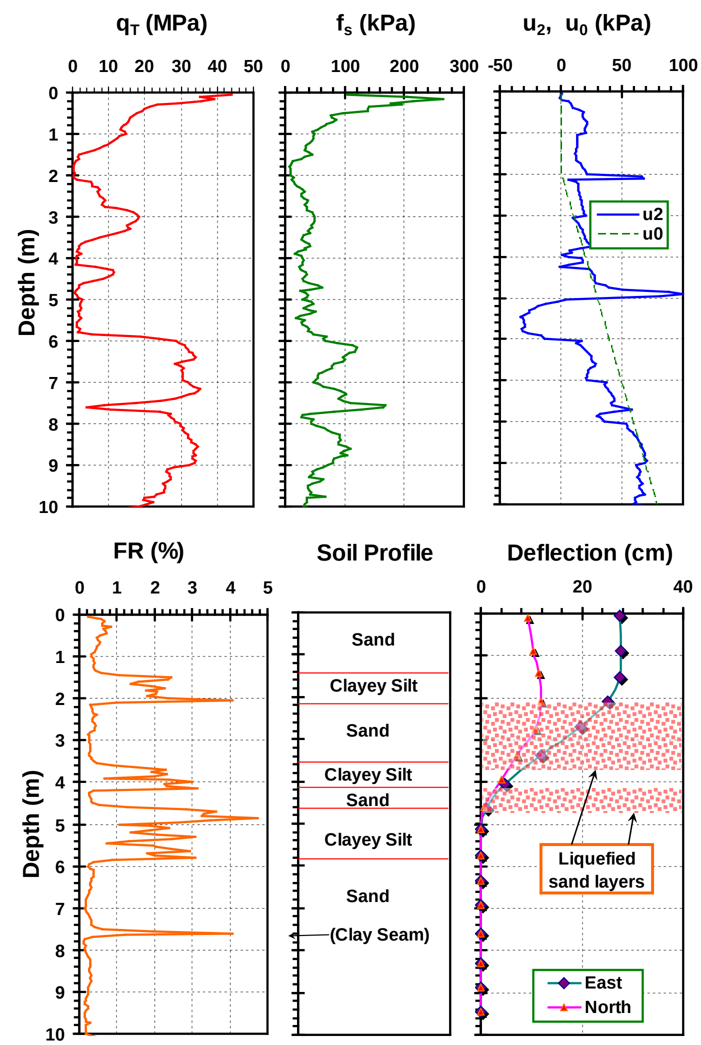


Fig. 3. Representative CPT sounding performed at Moss Landing, CA, and deflection measured by a nearby inclinometer due to the 1989 Loma Prieta earthquake (Data from Boulanger et al., 1997)

Assuming a certain magnitude, the critical PGA that can cause marginal liquefaction can be calculated using equation (3), and those based on q_T of the sounding performed at Moss Landing are shown in Fig. 4. The assumed magnitudes M_w are 6.0, 6.5, and 7.0, and for each assumed magnitude, the minimum critical PGAs are at the depth of 3.5m, 4.2m, and 4.5m, all of which are within the two sand layers that have been identified as having liquefied by Boulanger et al. (1997). The minimum critical PGAs are plotted versus the magnitude in Fig. 5. These decrease with the increase of the magnitude, since the duration of ground shaking is usually longer for larger earthquakes, which requires a lower PGA to trigger liquefaction. Also plotted in Fig. 5 is the attenuation relationship of the mean PGA and the mean PGA ± 1 standard deviation versus the magnitude based on equation (4) and (5), with the knowledge that Moss Landing is about 25 km away from the epicenter of the earthquake (Fig. 2). The minimum critical PGA curve meets the curve for mean PGA - standard deviation at the point of M_w = 6.95 and PGA = 0.19 g, while it meets the mean PGA + standard deviation at the point of M_w = 5.75 and PGA = 0.3 g. They indicate that in the event of marginal liquefaction at this site, the earthquake is likely of magnitude in the range from 5.75 to 6.95, and the PGA at this site is likely to be in the range from 0.19 g to 0.3 g. The data point corresponding to the mean values of these ranges is close to crossover point of the minimum critical PGA curve and the attenuation relation curve for the mean PGA, which corresponds to M_w = 6.4 and PGA = 0.24 g.

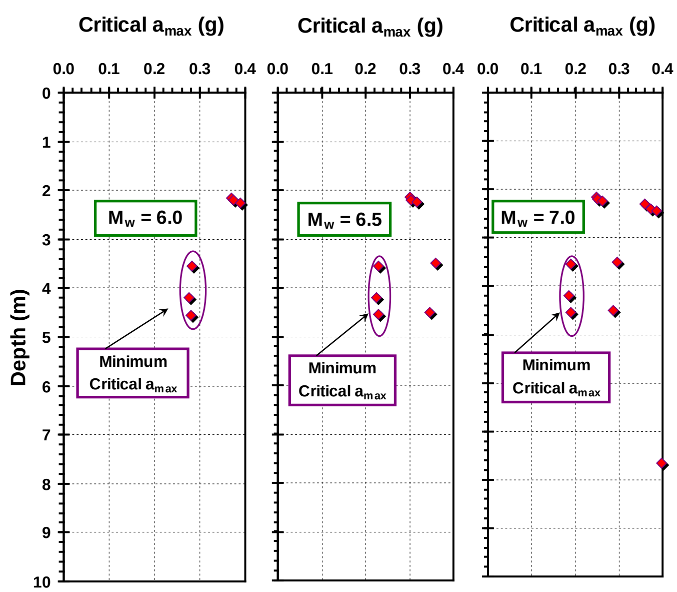


Fig. 4. Critical peak ground acceleration corresponding to earthquakes of different magnitude, based on tip resistance of the representative CPT sounding performed at Moss Landing, CA after the 1989 Loma Prieta earthquake

Evidence has confirmed that the Moss Landing site is a liquefied site. It is of moderate distance to the epicenter among the liquefied sites as shown in the regional map of liquefaction-induced damage in Fig. 2. Therefore, the Moss Landing site should have experienced CSR greater than CRR of the local soils, hence, greater PGA than the critical PGA that triggers marginal liquefaction. The M_w and PGA corresponding to the crossover point of the minimum critical PGA curve and the attenuation relation curve for the mean PGA (Fig. 5) can serve as the mean of lower boundaries of the magnitude of the 1989 Loma Prieta earthquake and the PGA at this site has experienced during this event. Thus using the proposed methodology, the 1989 Loma Prieta earthquake is very likely to have a magnitude greater than 6.4, and the PGA at this site is very likely to be over 0.24 g. These estimations are consistent with the real magnitude (M_w = 6.9 to 7.0) of the 1989 Loma Prieta earthquake and the PGA of 0.2 to 0.3 g at Moss Landing estimated by Boulanger et al. (1997).

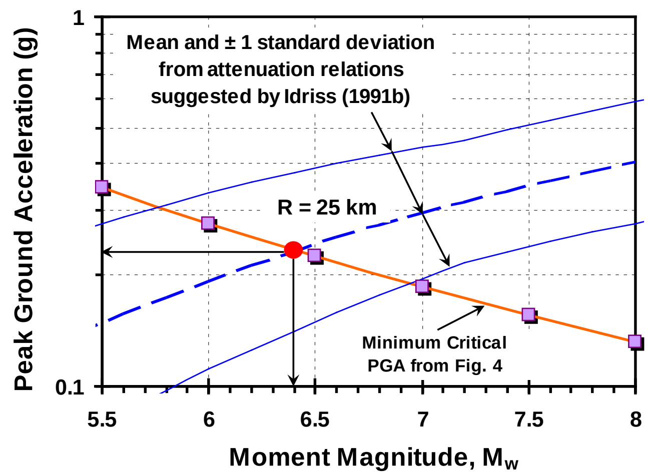


Fig. 5. Relations between moment magnitude and critical peak ground acceleration triggering marginal liquefaction at the Moss Landing Site, superimposed with the attenuation relation

Yerba Buena Cove Site

The Yerba Buena Cove (YBC) site is the primary work site during the study of liquefaction response of the fill soils along the waterfront area of San Francisco, CA after the 1989 Loma Prieta earthquake (Chameau et al., 1991a). Since the YBC site is one of the few liquefied sites that have the greatest distance to the epicenter (Fig. 2), the PGA this site experienced during the earthquake should be close to the critical PGA that can trigger marginal liquefaction. Figure 6 presents the results of the CPTu sounding performed at the YBC site after the earthquake in March of 1990, as well as the soil profile interpreted by Chameau et al. (1991a). The YBC site consists of approximately 3 m of gravel fill overlying a dune sand deposit of 5 m in thickness. The dune sand is underlain by a thick Bay mud layer, 18 to 21 m thick, which rests above the bedrock.

The back-calculated critical PGA corresponding to earthquakes of assumed magnitudes of 6.5, 7.0, and 7.5 is presented in Fig. 7, and the minimum critical PGA appears to be situated at about the depth of 6.6 m. Similar to the Moss Landing site, the minimum critical PGA is plotted against M_w in Fig. 8, superimposed with the attenuation relations suggested by Idriss (1991b). The crossover points between the minimum critical PGA and the mean PGA ± 1 standard deviation curves suggest that the M_w of the causative earthquake is likely to be in the range from 6.5 to 7.35, and the PGA the YBC experienced during the earthquake is in the range from 0.11 to 0.17 g. The M_w and PGA corresponding to the crossover point of the minimum critical PGA curve and the attenuation relationship for the mean PGA (Fig. 8) can serve as the mean of the estimated M_w and PGA. Thus, using the proposed methodology, the 1989 Loma Prieta earthquake is very likely to have a magnitude around 6.95, and the PGA at this site is very likely to be 0.13 g. The estimated M_w is consistent with the real magnitude (M_w = 6.9 to 7.0) of the 1989 Loma Prieta earthquake. The estimated PGA is also close to the computed PGA, which is about 0.17 g, based on numerical simulation carried out by Chameau et al. (1991b).

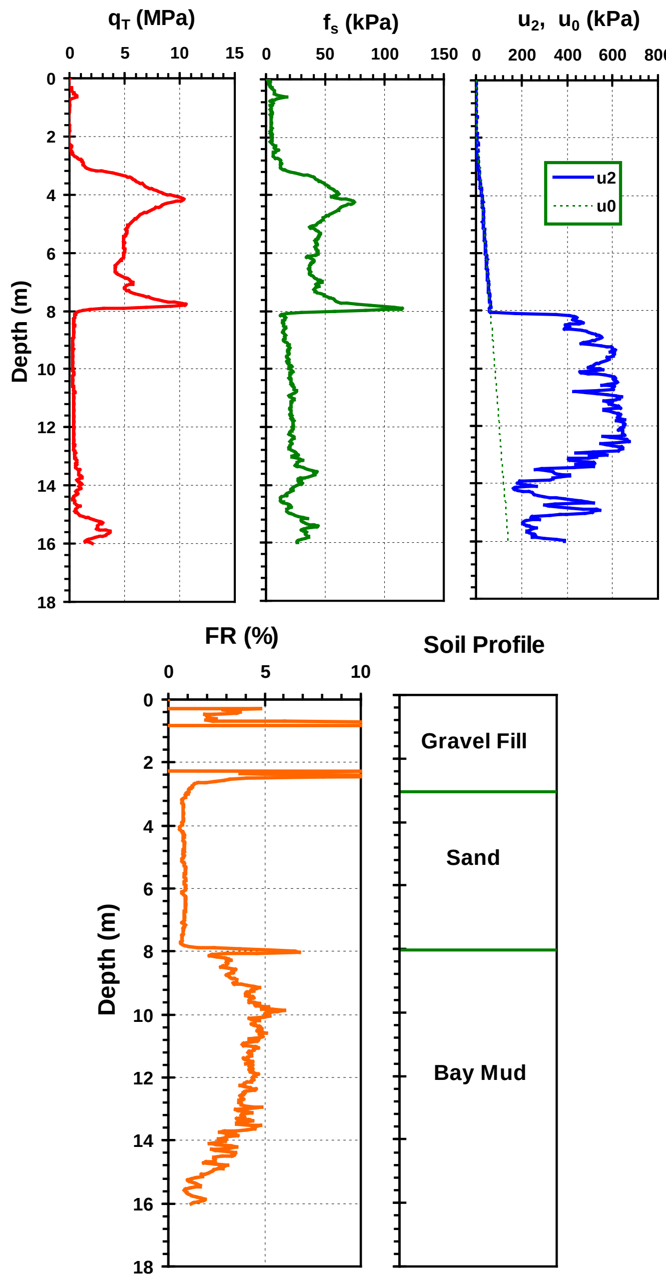


Fig. 6. Representative CPT sounding performed at Yerba Buena Cove site located in San Francisco, CA after the 1989 Loma Prieta earthquake (data from Chameau et al., 1991b)

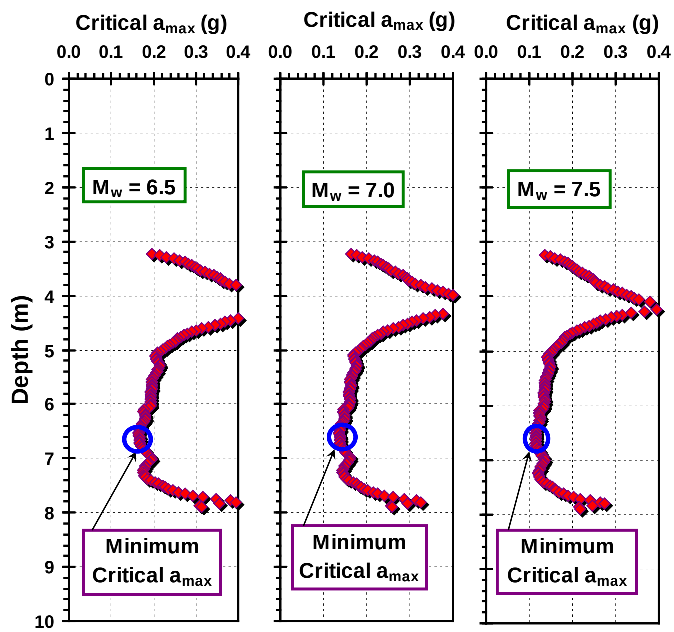


Fig. 7. Critical peak ground acceleration corresponding to earthquakes of different magnitude, based on tip resistance of the representative CPT sounding performed at Yerba Buena Cove site located in San Francisco, CA after the 1989 Loma Prieta earthquake

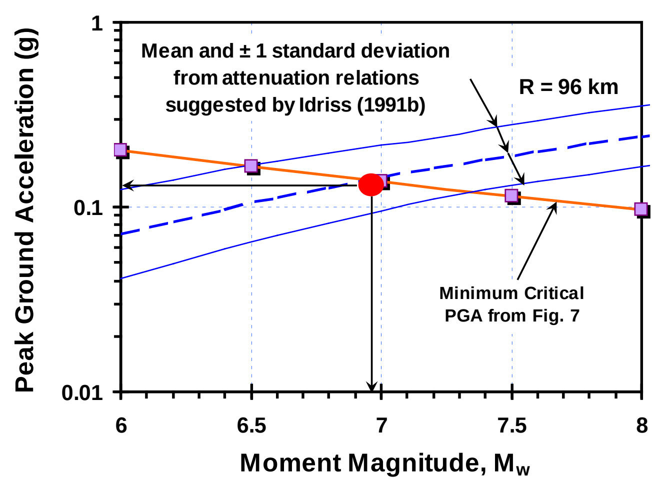


Fig. 8. Relationship between moment magnitude and critical peak ground acceleration triggering marginal liquefaction at the Yerba Buena Cove site, superimposed with the attenuation relation

The proposed methodology has been successfully applied to the Moss Landing site and the YBC site, both of which are the major sites where researchers investigated the liquefaction response of soils using CPTu tests, following the 1989 Loma Prieta earthquake. Based on the post-earthquake CPTu data from the Moss Landing site, the proposed methodology gives reasonable lower boundaries for the M_w of the earthquake and the PGA this site experienced during the earthquake. Using the CPT sounding performed at the YBC site after the earthquake, the M_w and the PGA derived from the proposed methodology are close to the real values. Although Idriss (1991b) suggested significant standard deviation in the attenuation relations for soft soil sites, the use of the mean PGA in attenuation relations was successful in matching the estimated M_w with the real M_w of the earthquake.

VALIDATION AND APPLICATION OF THE METHODOLOGY IN THE NMSZ

By observing the sedimentary characteristics of sand blows and large dikes in the NMSZ, Tuttle (1999) concluded that the liquefaction features found in the region resulted from a few very large earthquake events, instead of many smaller events. The large earthquakes of similar magnitude as those in 1811-1812 also occurred around 1450 AD, 900 AD, and 490 AD (Tuttle, 1999). These earthquakes consisting of multiple individual earthquake events occurred a long time ago, when no seismograph records were yet available, thus making paleoliquefaction analysis more complicated in the NMSZ.

Wolf River Site

The Wolf River site is a paleoliquefaction site (Broughton et al., 2001) located east of Memphis, TN, and north of Colliersville, TN, and situated on the north bank of the Wolf River. As shown in Fig. 9, the distance between the Wolf River site and the epicenters associated with the three big earthquakes in 1811-1812 are R = 100 km, R = 135 km, and R = 155 km, respectively.

At this location, CPT soundings were performed in areas having evidence of marginal liquefaction, as well as in non-liquefied areas (Obermeier, 2002). Among the seven soundings performed at the Wolf River site, soundings WOLF1 to WOLF4 were performed at sites where no liquefaction was observed, while WOLF5 to WOLF7 were at sites with only very small dikes extending upward into the overlying layers, which are the evidence of marginal liquefaction caused by the great New Madrid earthquakes of 1811-1812 (Van Arsdale, 1998). The soundings performed at sites of marginal liquefaction can be used to estimate the M_w of the earthquake and the PGA this site experienced. In addition, those CPTs that were performed at sites where there was no apparent liquefaction evidence provide a basis to estimate the upper boundaries of the M_w and PGA.

Figure 10 shows the SCPTu data for the sounding WOLF5, including the shear wave velocity V_s. Apparently, two sand layers exist in the depth ranges from 3.5 m to 10.2 m and from 17 m to 28 m, for their measured porewater pressure u_2 is close to the static porewater pressure u_0 and their friction ratio FR is relatively low, around 2%. The top 3 m of soil profile consists of fine-grained materials, underlain by an upper sand layer of about 7 m in thickness, where both q_T and V_s are relatively low. Small sand dikes, which formed the evidence of marginal liquefaction at this site, were found to erupt from the underlying sand layer into the top layer.

Fig. 9. Map showing the epicenters of the 1811 -1812 earthquake events and their distance to the Wolf River site near Memphis, TN

Assuming earthquakes of different magnitudes ranging from M_w = 7.5 to 8.5, Fig. 11 shows the critical PGA that could trigger liquefaction at the corresponding depth based on q_T and V_s. The minimum critical PGAs derived from both approaches are within the sand layer in the depth range from 3.5 to 10.2 m. Figure 12 plots the minimum critical PGA curves derived from q_T and V_s, respectively. Since the distance from the epicenters to the Wolf River site is known, the attenuation relations suggested by Boore & Joyner (1991) for deep soil sites in eastern north America can also be plotted in Fig. 12. Here, only the case for R = 100 km is plotted, for the attenuation relation curves with R = 135 km and R = 155 km do not intersect the minimum critical PGA curve at reasonable magnitude. The minimum critical PGA curves intersect the attenuation relation curve for R =100 km at the magnitude of 8.2 and 8.3, and the corresponding PGAs are about 0.125 g. It indicates that the marginal liquefaction features at this site are attributed to the December 16, 1811 earthquake event, which epicenter is 100 km away. The estimated M_w using the proposed methodology agrees with that suggested by Johnston (1996), who believed the December 16, 1811 earthquake event is of magnitude 8.1 ± 0.3 based on contemporary records of structure damage and human reaction.

The SCPTu sounding WOLF1 was performed where no apparent liquefaction evidence was found. Figure 13 presents the data from this sounding, and the measured porewater pressures u_2 are significantly higher than the static porewater pressure u_0 in the depth range from 14 to 19 m, indicating a clayey layer. In the depth range from 4 to 14 m and from 19 to 24 m, the q_T is relatively high, the u_2 is close to the u_0, and the FR is relatively low, indicating sandy layers.

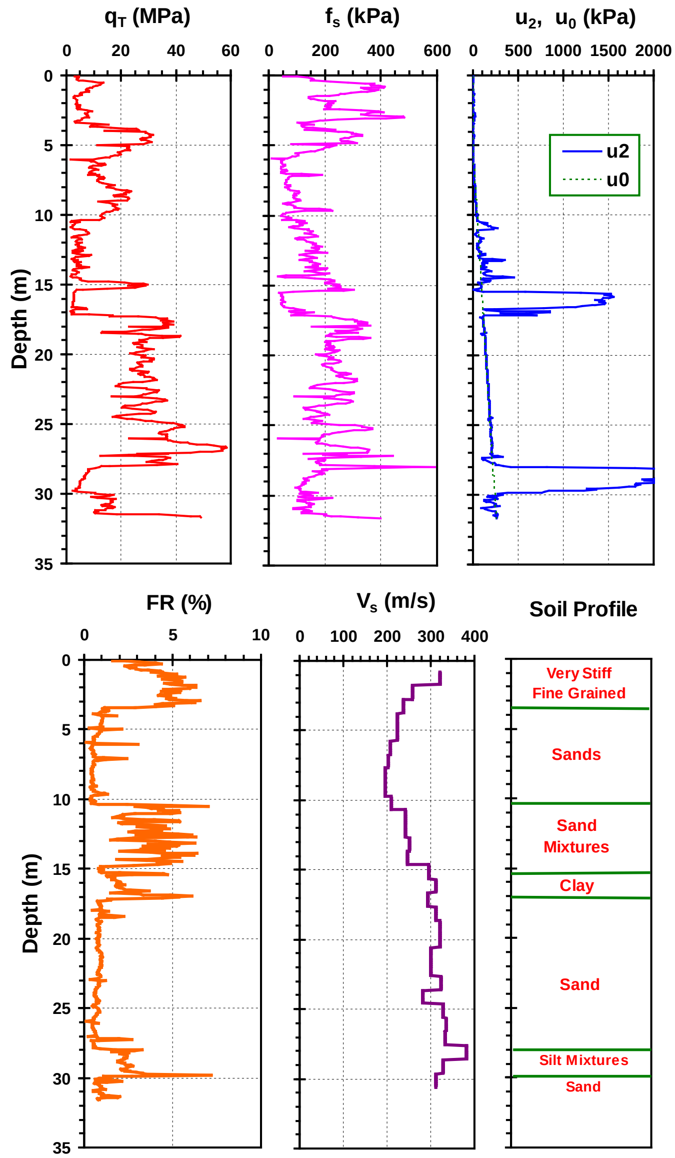


Fig. 10. Results of the sounding (WOLF5) performed along Wolf River, Memphis, Tennessee

Figure 14 shows the critical PGA in the event of earthquakes of different magnitudes from M_w = 7.5 to 8.5. The minimum critical PGA seems to be within the sand layer in the depth range from 19 to 24 m. Similar to the previous case studies, the minimum critical PGA curves are superimposed with the attenuation relation in Fig. 15. Since only the attenuation relation curve with respect to R = 100 km intersects the minimum critical PGA curves at magnitudes in reasonable range, the other attenuation curves associated with R = 135 km and R = 155 km are not plotted in this figure. The two crossover points between the minimum critical PGA curves and the attenuation curve correspond to M_w = 8.25, PGA =0.122 g and M_w = 8.4, PGA = 0.127 g, respectively. Because no liquefaction evidence was found at the location where this sounding was performed, the magnitudes and PGAs associated with the crossover points can serve as the upper boundaries of the real values. If the average value of the two crossover points is used, the upper boundaries for the M_w of the December 16, 1811 earthquake event is about 8.3 and that for the PGA of the Wolf River site is 0.125 g. The derived upper boundary of the M_w is also consistent reasonably well with the M_w suggested by Johnston (1996).

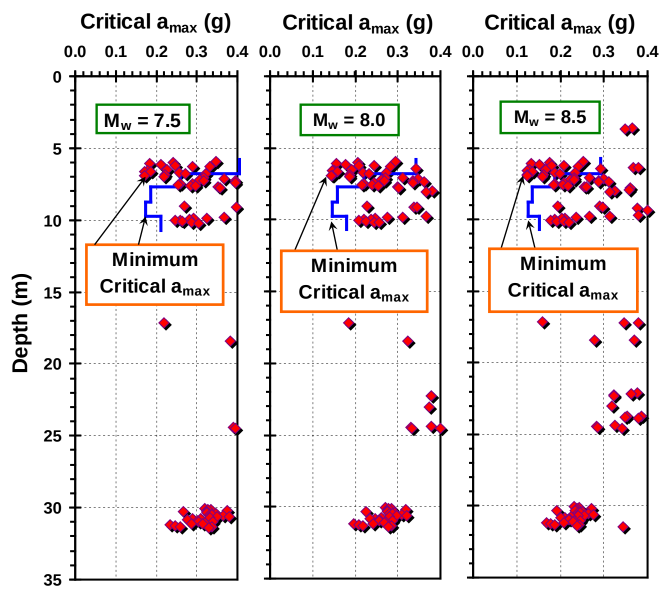


Fig. 11. Critical peak ground acceleration corresponding to earthquakes of different magnitude, based on the tip resistance and shear wave velocity of the WOLF5 sounding performed along Wolf River, Memphis, TN

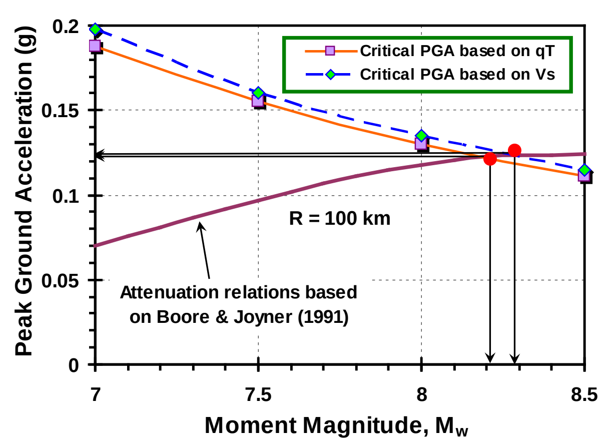
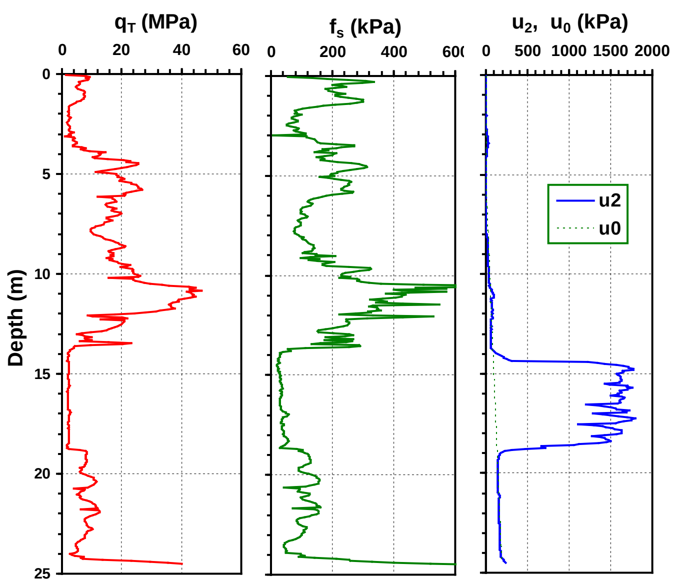


Fig. 12. Relations between moment magnitude and critical peak ground acceleration of possible previous earthquake triggering liquefaction at the WOLF5 site, superimposed with attenuation relations

Walker Site

The Walker paleoliquefaction site is located in Marked Tree, Arkansas. On the basis of radiocarbon dating and artifact analysis, the sand blows and related dikes at this site can be attributed to the large New Madrid earthquakes that occurred in circa 1530 A.D.. Although the full extent of the 1530 A.D. liquefaction field has not yet been determined, this is the southernmost known occurrence of sand blows of this age. Therefore, the estimated M_w and PGA based on this site should be close to the real values.

Figure 16 shows the magnitude and interpreted liquefaction fields for two seismic events circa 1530 A.D.. The epicenters of the corresponding earthquakes are assumed to be located at the centers of the liquefaction fields. The Walker site is approximately is 73 km and 110 km to the estimated epicenters of the two A.D. 1450 events, which were estimated to be of magnitude 7.6 and 8.0, respectively, by Tuttle (1999) based on the comparison of liquefaction features caused by previous and modern earthquakes.



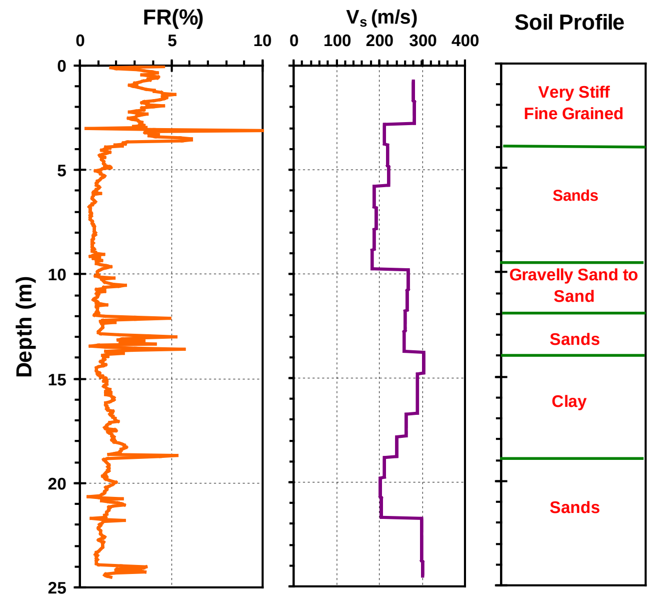


Fig. 13. Data representation for the sounding (WOLF1) performed along Wolf River, Memphis, TN

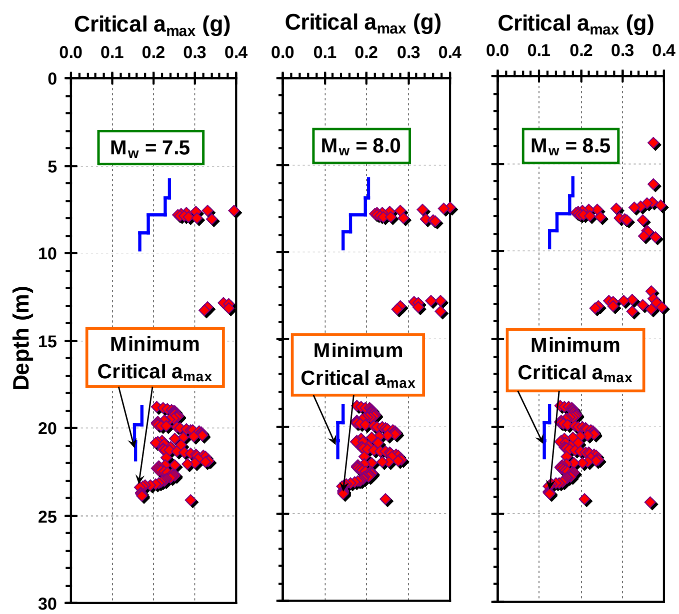


Fig. 14. Critical peak ground acceleration corresponding to earthquakes of different magnitude, based on the tip resistance and shear wave velocity of the sounding (WOLF1) performed along Wolf River, Memphis, TN

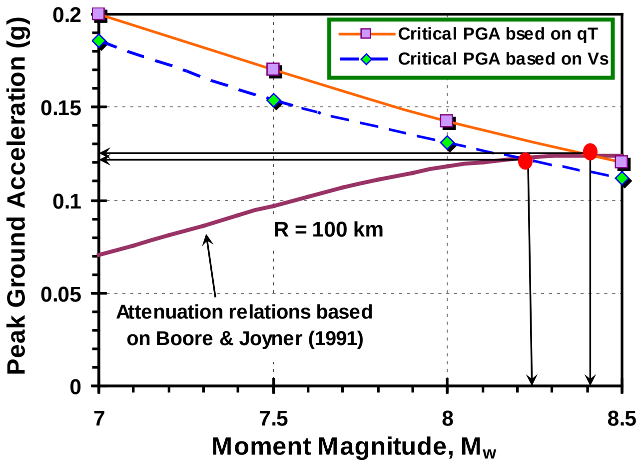


Fig. 15. Relationships between moment magnitude and critical peak ground acceleration of possible previous earthquake triggering liquefaction at the WOLF1 site, superimposed with attenuation relations

Figure 17 presented the data from a representative SCPTu sounding (MTREE01) advanced to a depth of 32 meters at the Walker site. From the back-calculated critical PGA based on q_T and V_s (Fig. 18), the minimum value occurs around the depth range from 18 to 20 m. The minimum critical PGA curves and the attenuation relation for R = 73 km are superimposed in Fig. 19, and the crossover points indicate M_w = 7.6 and PGA = 0.16 g. The attenuation relation for R = 110 km is not shown in this figure, for it does not intersect the minimum critical PGA curve at reasonable magnitude. Therefore, the liquefaction features at the Walker site was likely caused by the earthquake event which epicenter is 73 km away. Notably, the estimated magnitude by the proposed methodology agrees well with that suggested by Tuttle (1999).

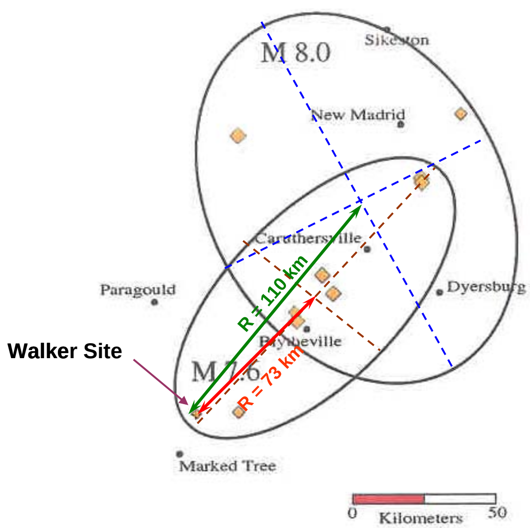


Fig. 16. Distance from the Walker site to the estimated epicenters of the seismic events that occurred around 1530 A.D. in NMSZ (after Tuttle, 1999)

CONCLUSIONS

Due to the relatively long recurrence interval of large earthquakes in the NMSZ, the historic and pre-historic earthquakes, especially the liquefaction features resulting from these earthquakes, are often used to extend our understanding of the seismic activities in this region. The lack of seismograph readings from the last large events in 1811-1812 compounds the problem. Some geotechnical methods, such as the simplified procedure based on in-situ data, have been proven very useful for estimating the seismic parameters associated with previous earthquakes.

Criteria have been developed to evaluate the capacity of the soil to resist liquefaction (i.e. CRR) based separately on the cone tip resistance q_T or shear wave velocity V_s. Since all the test data used in developing the criteria are collected after the corresponding earthquakes, the criteria are more appropriate for estimating the seismic parameters associated with previous earthquakes.

A new methodology is proposed to estimate the seismic parameters (moment magnitude M_w and peak ground acceleration PGA) associated with previous earthquakes, using the simplified procedure based on SCPTu data and the attenuation relationships developed for the corresponding seismic areas. This methodology is initially validated through the paleoliquefaction studies at two sites associated with the 1989 Loma Prieta earthquake (Moss Landing and Yueba Puena Cove). After verification, the procedures are applied to estimate the M_w and PGA for the major previous earthquakes in the NMSZ. Two sites are constrained: Wolf River site, TN (1811 – 1812 events); Walker site, AR (1530 A.D. events) in this paper. Similar analyses on other sites in the NMSZ were documented in Liao (2005). Although the methodology is theoretically simple, the estimated earthquake magnitudes and associated PGAs agree quite well with the records and values estimated by other methods.

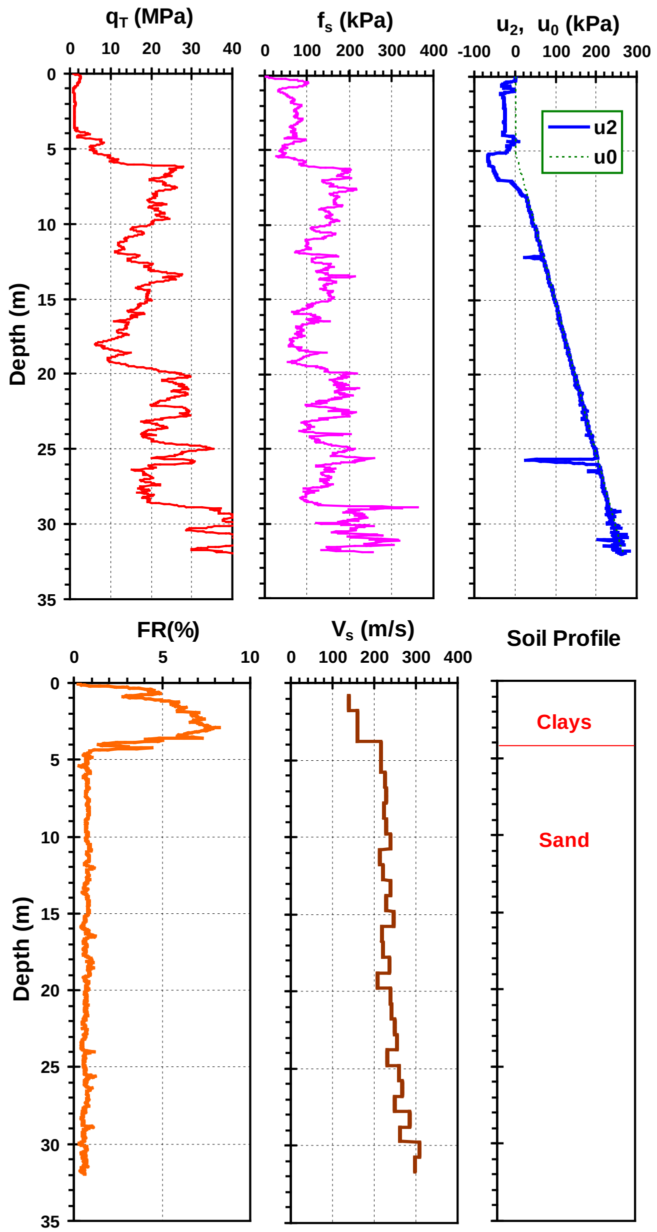


Fig. 17. Data representation for the sounding (MTREE01) performed at the Walker site, Marked Tree, Arkansas

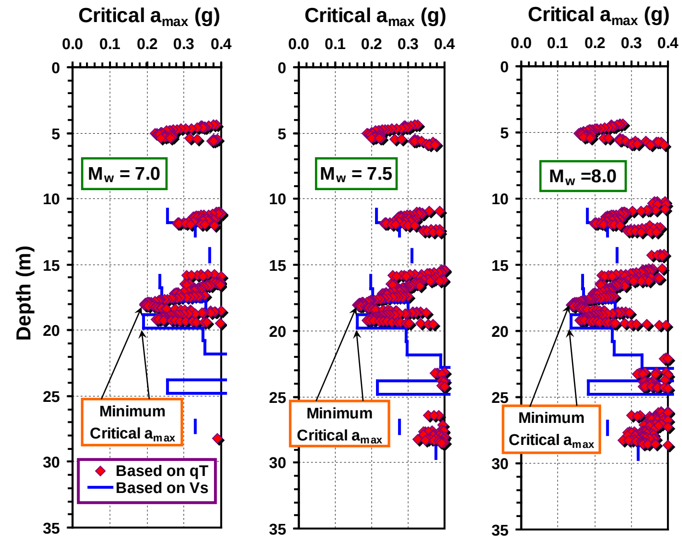


Fig. 18. Critical peak ground acceleration corresponding to earthquakes of different magnitude, based on the tip resistance and V_s profile from SCPTu sounding MTREE01

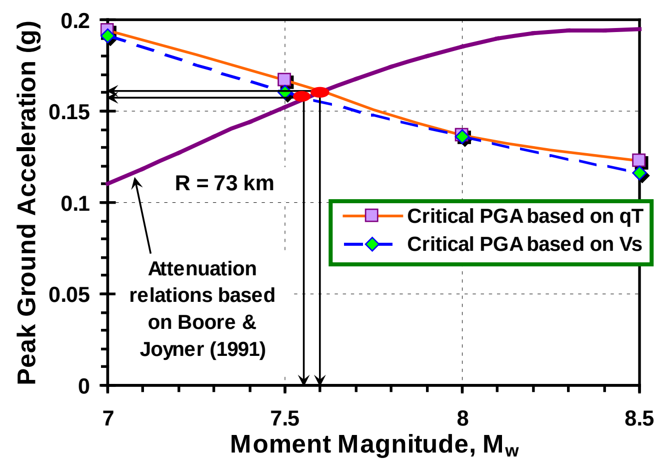


Fig. 19. Relationship between moment magnitude and PGA of possible previous earthquake triggering liquefaction at the Walker site based on the MTREE1 sounding, superimposed with attenuation relations

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